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Simons,
D. B.

ESTIMATION OF PARAMETERS THAT DESCRIBE CHANNEL GEOMETRY FOR WATERSHED MODELING

CONTRACT NO. 16-712.01-CA

Prepared for

USDA FOREST SERVICE

ROCKY MOUNTAIN FOREST AND RANGE

EXPERIMENT STATION

Flagstaff, Arizona

Prepared by

Civil Engineering Department
Engineering Research Center
Colorado State University
Fort Collins, Colorado

D. B. Simons
R. M. Li
T. J. Ward

December, 1978

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AUTHORIZATION

This research was sponsored by the U. S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station and supported with Colorado State University matching funds. The investigations were conducted in accordance with Research Agreement No. 16-712.01-CA between the Rocky Mountain Forest and Range Experiment Station and Colorado State University. D. Ross Carder was the authorized project leader for the Rocky Mountain Forest and Range Experiment Station and Daryl B. Simons and Ruh-Ming Li were the principal investigators for Colorado State University. The period of agreement was from January 10, 1977 to September 30, 1977. This report was first distributed in December 1977 and revised in December 1978.

In accordance with the study plan, the report on estimation of parameters that describe channel geometry for watershed modeling is submitted.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

1.1 General

Numerical models for simulating water and sediment yield from watersheds have provided a useful means for studying environmental and engineering problems. Models based on numerical formulations of the individual physical processes are more advantageous than other models. Advantages include utilization of input variables that have physical significance and are not stationary in time and space. All model types, however, do require input data that describe the area being modeled. These data include the physiography and geometry of the land surface and drainage system, vegetation and soil characteristics, and climatic records. Development of an adequate data base for numerical models can be very time consuming and costly. Acquisition of data for nonurbanized or remote watersheds is particularly difficult because of a lack of base line information and limited accessibility. Data for these areas are usually obtained after extensive field sampling and measurements and office analysis.

As the size of the area, the number of parameters being measured, and intensity of sampling increases, so does the time and cost of modeling. One method of rapidly surveying a watershed utilizes a remote sensing technique. Using ground, aircraft, or satellite based platforms, the remote sensing equipment allows rapid sampling of reflected and emitted energy from the environment. Results of remote sensing can include black and white and color photography, color infared photography, multispectral scans, and thermal scans. The oldest and most used products of remote sensing are black and white, color, and color infared photography. These photographs are often acquired from aircraft based sensing platforms. This procedure has been extensively used in

engineering, forestry, geology, land use management, and agriculture. Presently, photographs collected through use of aircraft offer optimum coverage without losing essential features as compared to satellite and land-based acquisitions. This is particularly important in watershed studies where a broad overview of selected drainages is necessary while not overlooking important details. Aerial photograph acquisition can be conducted for remote areas almost anytime during the year. Until further advances in satellite based acquisition are made, aerial photography is perhaps the most realistic method for collecting information to be used in developing a data base for numerical models.

A variety of information can be extracted from aerial photography including channel geometry, soil types, geologic features, vegetative types and cover conditions, and location of hydrologically important areas. As a check on the accuracy of information obtained from aerial photography, and in order to collect other information, ground truth data acquisition is necessary even if executed in a cursory manner.

1.2 Need for Numerical Models

As man's influence extends to remote areas, a better assessment of the consequential impacts is necessary. Numerical models, particularly physical process simulation types, provide a method for estimating these impacts. These models require adequate base line data for operation. Therefore, what is needed is a defined methodology for collecting and analyzing data that provides an adequate information base for model operation.

1.3 Scope of Present Study

This study does not attempt to design a total methodology for development of a complete information base. Instead, methodology is presented for estimating important channel geometry parameters. The methodology also presents techniques that can be utilized in the field and office. The recommended field techniques are applicable to ephemeral streams but may not be useful for some perennial streams. The test area for this study was the Woods Canyon Watershed, Coconino National Forest near Flagstaff, Arizona.

II. CHANNEL GEOMETRY EQUATIONS

2.1 Equation Form

An estimation of channel geometry parameters is essential for mathematical models that route water and sediment from watersheds (Li, 1974; Simons, Li, and Stevens, 1975). These parameters can be derived from the channel cross-section shape or empirically determined. Primary consideration for this study will be given to those parameters that describe the relationship between the wetted perimeter, p, and the flow area, A. The desired result is a functional relationship

$$p = f(A) \tag{1}$$

where f(.) can be a power function, polynomical, or other form. Again, the constants describing the relationship can be derived theoretically or by empirical methods.

According to Li, Simons, and Stevens (1976), most natural channels in upland watersheds are shaped by water discharge, dominant size of the bed particle, and the forces applied to the particles. The theoretical development by Li et al. (1976) supports the power relation form of Equation 1 or

$$p = aA^b \tag{2}$$

where a and b are constants determined from channel geometry based on field measurements. The coefficient a is quite variable and dependent on the cross sectional geometry, while b can be theoretically derived as 0.5 (Li et al., 1976).

The methodology developed for this report is based on acquisition and analysis of actual cross-sectional data and does not rely on theoretically determined values. The following sections present techniques for data collection and analysis of channel cross-sectional information.

2.2 Collection of Field Data

Data needed for the development of Equation 2 are horizontal and vertical distances that describe the cross-section. Horizontal distances are measured from a datum point, such as a bank-full discharge water mark from one bank to the other (Plate 1).

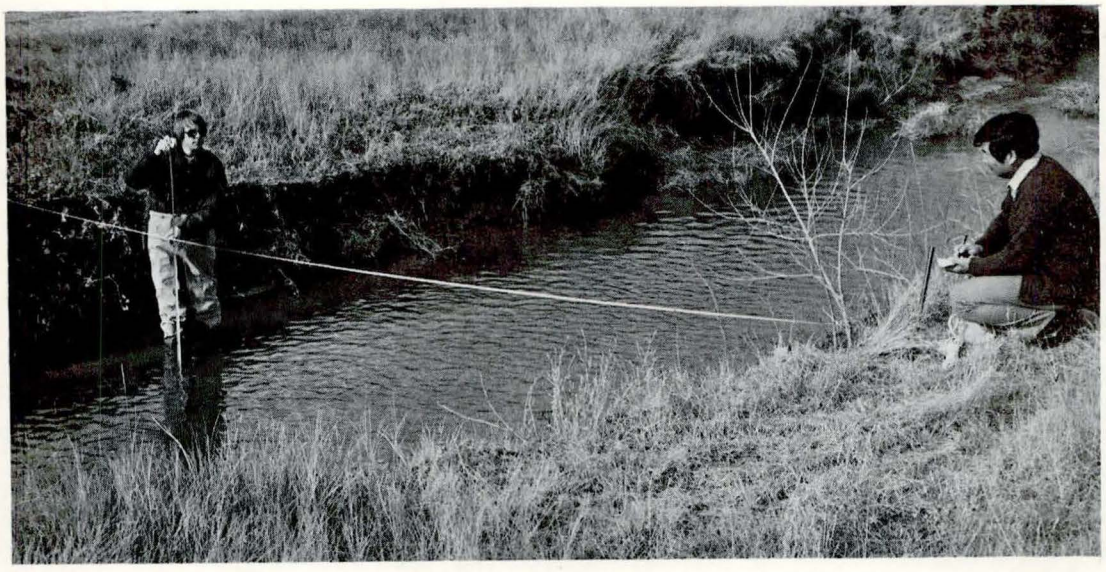


Plate 1. Taut tape method for measuring horizontal distances.

Whenever practical, it is recommended that the starting point begin at the left bank facing downstream. Horizontal measurements should be perpendicular to the channel cross-section. Vertical measurements must be referenced to the same datum, such as the horizontal measurement line or the top of the bank. There are several techniques for measuring the required horizontal and vertical distances. In small watersheds where streams are either dry or otherwise wadable, the taut tape and the stadia rod method can be utilized. When applicable about 10 data points should be taken.

2.2.1 Taut Tape Method

The easiest measuring technique to use is the taut tape method. Where stream widths are normally less than 100 feet, a taut tape or marked rope can be stretched across the stream as shown in Plate 1. Care must be taken to insure the tape is level since it serves as the datum for vertical measurements. Starting from the datum bank, measurements are taken at horizontal intervals fixed by the geometry of the channel. At each measurement point, the distance from the datum to the stream bed is measured. This results is a set of measurements of a vertical distance corresponding to the horizontal distance from the starting point.

2.2.2 Stadia Rod Method

Use of a stadia rod and transit or hand held level is a more sophisticated measuring technique. The hand held level is described because it is the simplest method. When using the hand held level, the observer stands on the datum bank mark and the distance between the mark and the eye of the observer is measured and recorded (Plate 2).

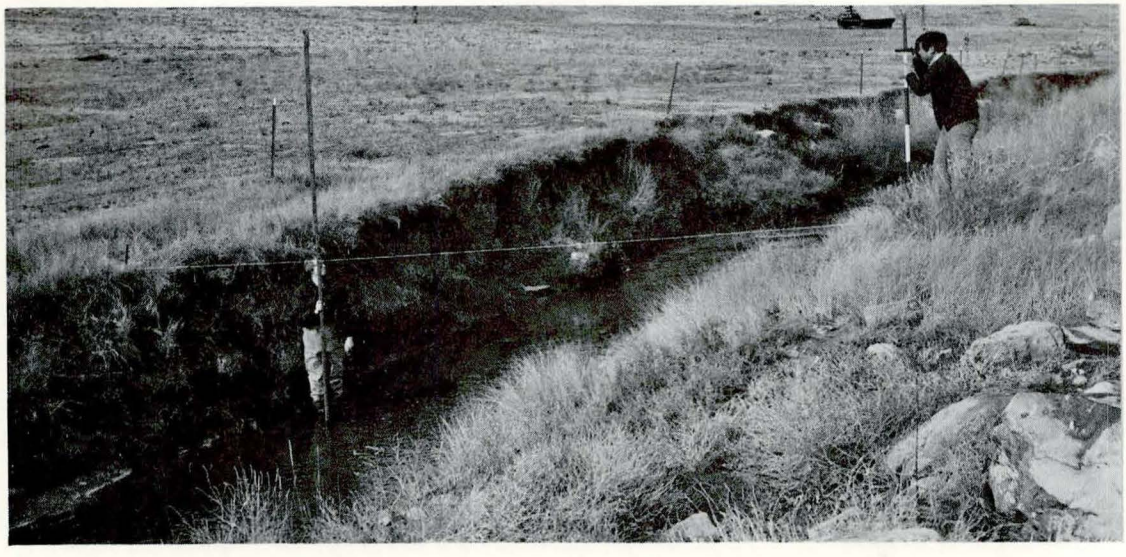


Plate 2. Hand held level for measuring horizontal distances.

To insure a constant level position, it is helpful to provide the observers with a staff or extra stadia rod that the level can be held against at a constant distance above the datum mark. An assistant holding a stadia rod proceeds across the channel perpendicular to the observer. A perpendicular sampling line should be laid before actual measurements begin to serve as a guide to the assistant. A marked rope or steel tape provides an adequate sampling line.

The assistant proceeds along the sampling line stopping at predetermined points. At each point, the observer reads the rod through the hand held level, noting the level and stadia hair difference. The stadia hair difference is the difference as determined by upper and lower cross hairs in the hand held level. For example, if at station 4 the observer reads 7.137 on the upper cross hair, 7.025 on the middle cross hair, and 6.913 on the lower cross-hair, the stadia hair difference is 7.137 - 6.913 = 0.224 units. This value is then multiplied by the stadia constant that is inherent in each type of survey instrument. A common stadia constant is 100. For the example above, the horizontal distance from the datum is 0.224 x 100 = 22.4 units. If the eleveation of the hand held level is 5.146, then the vertical distance below the datum for this example is 7.025 - 5.146 = 1.979 units. Again, the set of data consists of horizontal distances from the datum bank mark and vertical distances below the mark. This procedure will accurately work only if the observer stands at the datum bank mark end of the sampling line, the level is held steady, and the vertical position of the level does not vary.

The number and spacing of cross-sections where data is to be gathered is dependent on changes in channel geometry, time and financial

constraints, and the level of accuracy required. Ideally, there would be cross-sectional data on every important channel taken at regular intervals. However, this is seldom the case. More often, cross-sections are taken at important locations such as above and below confluences of major tributaries. Obviously, more cross-sectional information allows for increasing confidence in selecting a representative p and A relationship for each major channel. Because of the numerous factors that can influence the selection of cross-sectional sites, a complete set of selection criteria cannot be developed. However, some general suggestions can be made:

1) In model development determine the major channels, usually the primary ones, on topographic maps.

2) Select sites where significant changes in channel morphology occur, e.g. above and below confluences or long reaches of steep walled or shallow channels.

3) Select at least three cross-sections at each site at approximately equal distances from each other. Distances between cross-sections might be between 50 to 200 feet.

4) Take approximately 10 vertical measurements at each section.

Although general in nature, the above suggestions provide an initial methodology for planning and conducting data acquisition. Once collected, checked, and recorded, the data is then ready for analysis and development of the p and A relationship for each cross-section. This analysis is conducted using linear regression and computer applications.

2.3 Data Analysis and Equation Development

The collected and reduced data provides the information necessary for analysis. The desired result is a statistically significant equation in the form of Equation 2. This equation can be rewritten in the logrithmic form as

$$\ell np = \ell na + b\ell nA \tag{3}$$

which is recognizable as the linear equation

$$y = c + mx \tag{4}$$

where y is the dependent variable, c is an intercept value when $x = 0$, m is the rate of change slope of the linear equation, and x is the independent variable. In this case, $y = \ell np$, $c = \ell na$, $m = b$, and $x = \ell nA$. The values m and c can be estimated using the theory of least squares.

The data set of x_i and y_i and ℓnp_i can be extracted from the field information or remote sensing results. This is completed by vertically segmenting the cross section (Figure 1).

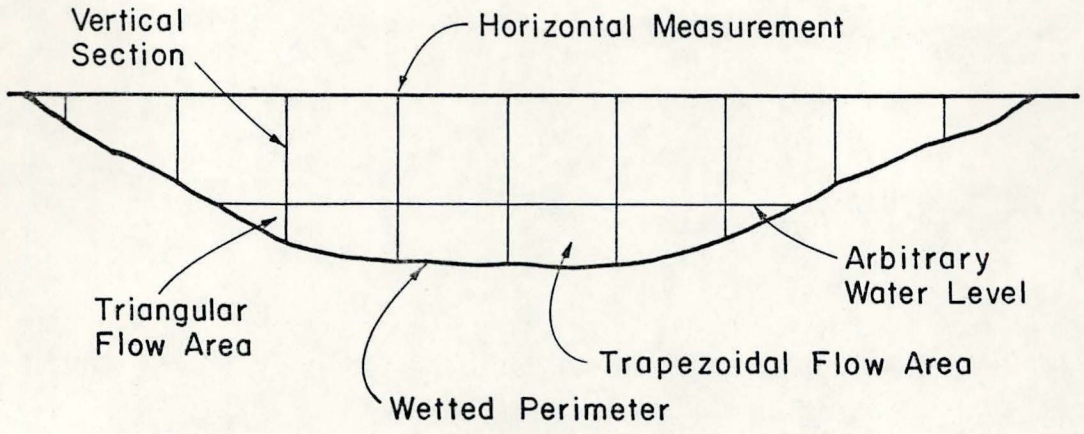


Figure 1. Typical channel cross section illustrating measurement lines, flow areas, and wetted perimeter.

For each layer depth, the corresponding area and wetted perimeter can be calculated from the geometry of each of the small segments. The geometry of each small segment is assumed to be either a triangle or a trapezoid. A triangular shape is assumed if the depth level intersects the segment at the highest bed elevation or between the highest and lowest elevations (Figure 1). A trapezoid is assumed if the depth level is higher than either bed elevation in the segment. The flow area and wetted perimeter is calculated for each segment. Then all the individual areas and wetted perimeters are summed to determine a total area and wetted perimeter at each flow depth. This can be represented for the area as

$$A_i = \sum_{j=1}^{n} A_{ij} \tag{5}$$

where A_i is the total cross-sectional area at level i and A_{ij} is the area at level i in channel sector j. Similarly for p_i, the wetted perimeter is

$$p_i = \sum_{j=1}^{n} p_{ij} \tag{6}$$

where the subscripts are the same as before.

A computer program has been written that calculates the previous quantities for input data of horizontal and vertical distnaces. The program CHANGEO Channel Geometry, is written in Fortran IV language (Appendix A). Appendix B contains a sample input-output of this program.

Once the data is reduced to p and A, relationships using program CHANGEO information for each individual cross-section must be

combined in a logical manner to provide a representative p and A relationship for the channel. There are several methods for determining a representative relationship, two of which are presented. One method averages the a and b parameters from Equation 2 for each of the cross-sections in the channel. This method, however, does not account for changes in discharge between widely spaced sites or the inherent variability of even nearby cross-sections. Another method weights the values of a and b by the down channel distance from the channel intersection with the watershed boundary. This represents change of discharge in a down channel direction. The disadvantage of this method is that numerous cross-sections are required. A compromise of these two approaches consists of selecting key channel reaches, collecting and analyzing cross-sectional data, and averaging the a and b parameters. The averaged parameters can then be distance weighted. This combined approach compensates for site variability and the effects of changing discharge. These computations can be formulated for the parameter $\hat{a}_c$ as

$$\hat{a}_c = \frac{\sum_{k=1}^{m} \frac{1}{n} \sum_{i=1}^{n} a_i \; {}_k \; d_k}{\sum_{k=1}^{m} d_k} \qquad (7)$$

where $\hat{a}_c$ is the estimated representative parameter of a for the channel, a_i is the individual a parameters from n cross-sections at k sites in the channel, and d_k is the channel distances from the channel intersection of the watershed boundary to a central point of the sampling site. This combination of the two methods uses the best attributes of each.

2.4 Limitations of Approach

There are two limitations to development of p and A relationships using the linear regression and computation procedures presented. First, the channel must be well defined with no distinct flood plain. Such a situation can produce large anomalies in the computations when the flow depth is above the edge of the regular channel bank. Fortunately in most forest watersheds, distinct channel floodplain areas do not exist. If floodplains exist, a separate p and A relation should be developed for the overbank condition. The second limitation is that the p and A relationship may hold only for the data range from which it was developed. Extension to areas above the maximum can lead to erroneous estimations of p. For this reason, original data collection should be based on a datum such as maximum discharge level or bank full flow. Choosing such a datum allows the developed equation to be used over the actual range of flow areas.

III. REMOTE SENSING DATA COLLECTION

3.1 Methodology

Data collection to provide input information for analysis can become quite time consuming and expensive for a large or inaccessible watershed. Use of remotely sensed imagery, particularly stereo photography can provide a data source for indirectly measuring necessary information. The approach presented here requires high quality, large scale overlapping aerial photographs of the stream channels and use of a stereocomparator. Data collection using a stereocomparator requires special skills but produces the highest quality of data relative to other measurement techniques. Original negatives of the stereo pair of aerial photographs are used to produce diapositivies that are mounted on the left and right stages of a stereocomparator. Analysis using this method was conducted on Colorado State University's WILD STK-1 Stereocomparator located at the Engineering Research Center, Foothills Campus (Plate 3).

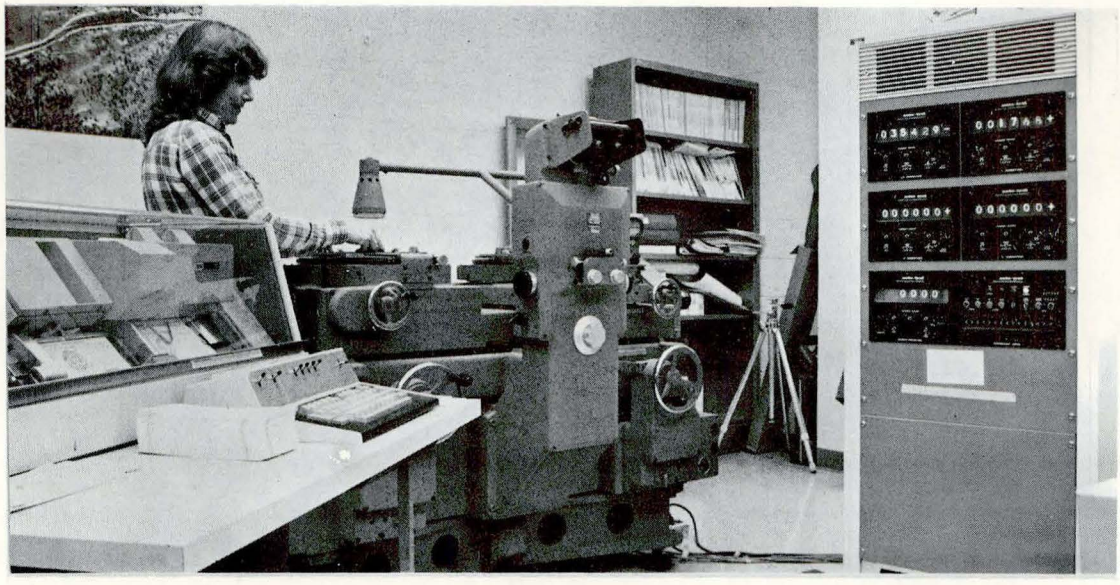


Plate 3. WILD STK-1 Stereocomparator (center) with output digitizer (right) and card punch (left).

The stereocomparator has the instruments to measure photo distances as small as one micron. The readings on the stereocomparator are connected to an analog converter that outputs the information on punched computer cards. Punched data for each measurement point includes the X and Y coordinates of the point and the parallax values of P_x and P_y for the point. The X and Y coordinates are used to determine horizontal distances and the P_x and P_y values are used to determine vertical distances.

The parallax is the apparent displacement of a point caused by a change in the observation site which, in this case, results from the movement of the airplane between the taking of photographs. Parallax is the characteristic of stereo photography that produces a three-dimensional effect. The parallax can be accurately measured by using the "floating mark" adjustment in the stereocomparator. The floating mark is a pair of small dots for the right and left photographs. These dots move together until they overlap and rest on the apparent ground surface, appearing to "float" above the ground or below ground if they do not precisely coincide with the surface elevation. The small adjustments needed to "place" the mark on the ground surface are measured and compared with the original readings for the datum point. Small adjustments can then be converted to elevation changes. With this method, the necessary horizontal and vertical measurements for development of the P and A relationship can be obtained.

Some values should be developed from ground measurements. These values help insure proper calibration of the stereocomparator for the measurement procedure. The most important value that should be developed is a ground control net, visible on the ground and in the aerial

photography. This control net should consist of three widely spaced points or landmarks, such as large boulders, fenceposts, or corners of buildings. On-ground measurements of distances between control points and elevations of each control point should be made. If impossible, measurements on small features of fixed length, such as bridges or targets, can be used but with some loss of accuracy. A third method of obtaining calibration values is to compute information using topographic maps and characteristics of the aerial photography. This approach may be the least accurate but most practical in terms of time and funding for large or isolated watersheds.

Equations for computing the horizontal and vertical distances are independent of the field method used to obtain control but the accuracy of the resultant distances are dependent on the accuracy of the ground survey. It should be noted that a poor quality aerial photograph will yield information that would be less accurate than high quality imagery.

The elevation of a picture control point can be used to determine the airbase B as

$$B = (H-h_c)\ \frac{P_c}{f} \tag{8}$$

where B is the airphoto base, H is the flight height above the control point elevation, h_c, P_c is the parallax of the control point, and f is the focal length of the airborne camera. The airbase B can also be obtained by measuring the on ground distance between two points and adjusting it to a distance measured on the aerial photographs. Once the airbase is known, the elevation of a point a can be computed as

$$h_a = H - \frac{Bf}{P_a} \tag{9}$$

which is Equation 8 in another form. The planar coordinates, X and Y, with respect to the aerial photograph photo-center, can be found from

$$X_a = B(\frac{x_a}{P_a}) \tag{10a}$$

$$Y_a = B(\frac{y_a}{P_a}) \tag{10b}$$

$$X_b = B(\frac{x_b}{P_b}) \tag{11a}$$

$$Y_b = B(\frac{y_b}{P_b}) \tag{11b}$$

where X_a, Y_a, Y_b, and Y_b are the planner coordinates of points a and b, x_a and y_b are the photo coordinates of the points and P_a and P_b are the parallaxes of the points. The horizontal distance between the points is then

$$\overline{AB} = \sqrt{(X_b - X_a)^2 + (Y_b - Y_a)^2} \tag{12}$$

where AB is the estimated on-ground distance between points a and b. The values of x_a, y_a, x_b, y_b, P_a, and P_b are obtained from measurements on the stereocomparator and then converted to on-ground distances. The elevations at each point, h_a and h_b, are compuated from Equation 9 and then compared to the elevation of the bank starting point datum h'. The difference between the two is the depth of the channel of

$$\Delta h_a = h' - h_a \tag{13}$$

where Δh_a is the distance below datum h' to point a. The set of data developed by Equations 12 and 13 comprise the information necessary for further analysis of cross-sectional geometry presented in Section II.

3.2 Limitations of Approach

There will be some loss of information in the transfer of data from imagery to estimated on-ground distances. Losses may be diminished by increasing the number of sampling points at each cross section on the aerial photograph. This will be highly dependent on the size and shape of the channel to be measured and the quality of imagery. It is recommended that no less than three in-channel measurements be made in order to provide the necessary information. Remotely sensed information, despite inherent problems, can provide an accurate, low-cost data base for obtaining necessary parameters for watershed models.

IV. APPLICATIONS

The methods presented in this report were applied to the ground surveys and aerial photography conducted on the Woods Canyon Watershed, Beaver Creek Experimental Watershed, Coconino National Forest near Flagstaff, Arizona. The Woods Canyon Watershed was chosen by the U.S. Department of Agriculture Forest Service as a benchmark drainage area. It was selected because of its undisturbed character and the proposed timber sales. Ground surveys were conducted on September 1 and 2, 1976 for 11 channel sites in the watershed. Aerial photography for parts of the main channel system was collected on November 3, 1976. Two sites had ground surveys combined with adequate aerial photography as shown in Figure 2. Ground survey information for these sites is presented in Table 1. This table shows the individual and average p and A relationship parameters at each site.

Several problems arose during analysis of the aerial photographs. One problem was excessive canopy cover of the channel. In two of the four ground truth sites photographed, the canopy blocked the aerial view of the channel banks. A similar problem arose from the low sun angle in the photographs. In some sections shadows obstructed the view of the channel resulting in inadequate imagery for precise measurements. Another problem developed because of inadequate ground control in the photographs. The lack of good ground control plus the low quality imagery caused concern with respect to the quality of data that can be extracted from the aerial photographs. However, actual results were much better than anticipated.

A series of three cross-sections were measured at each of the two sites. The data points for each cross-section were plotted and a sketch-

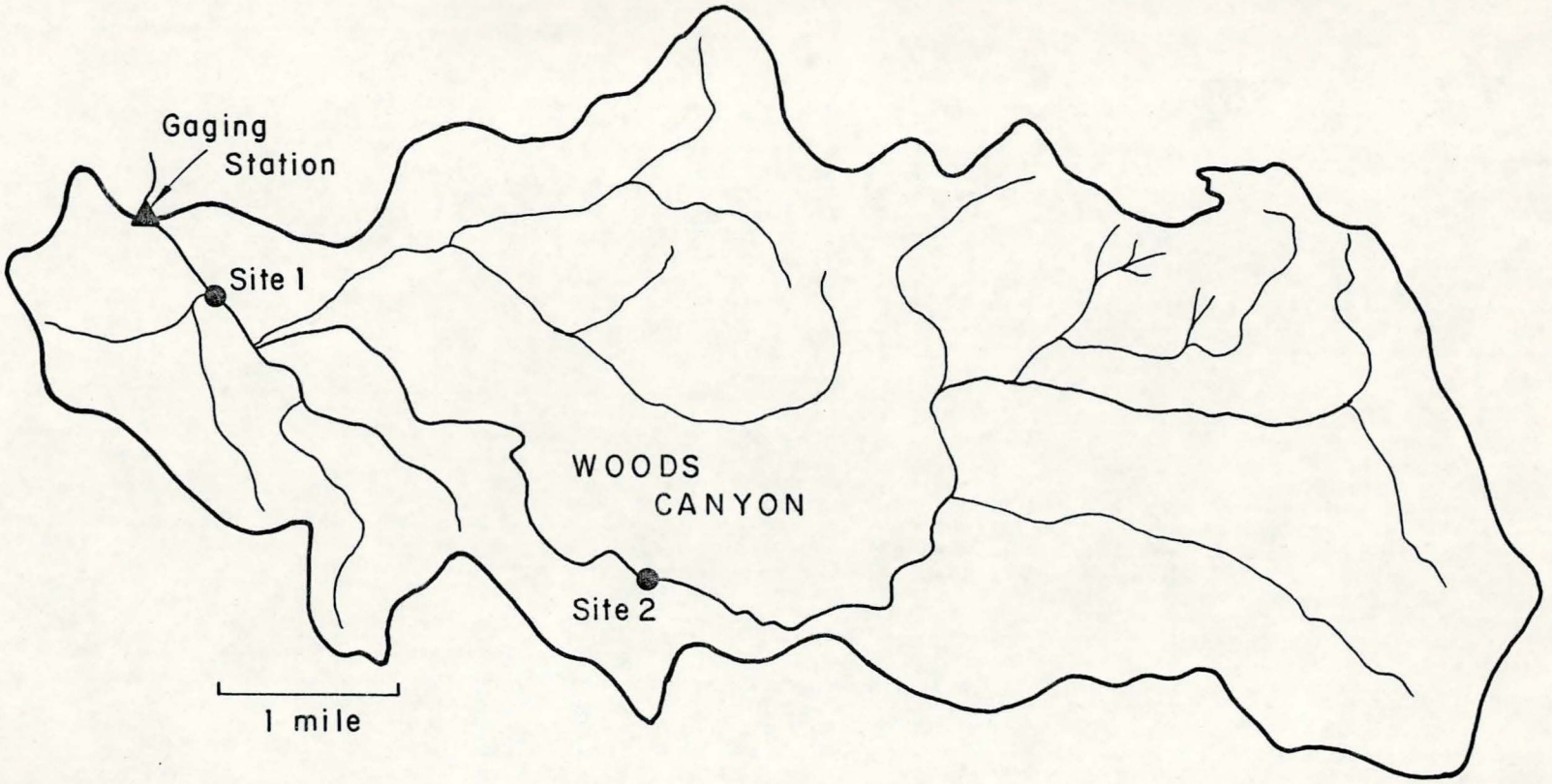
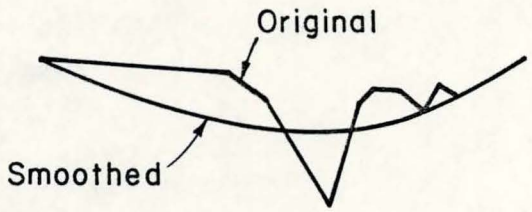


Figure 2. Outline map of Woods Canyon Watershed showing locations of Sites 1 and 2.

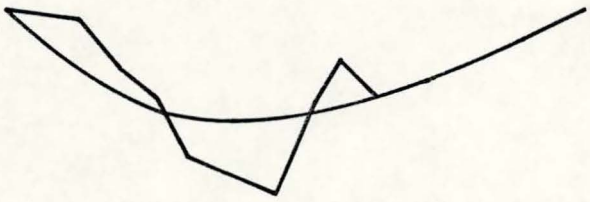
Table 1. Computer results based on ground surveys of channel cross sections.

Site	Section		Parameters in $p = aA^b$ a	b
1	1		16.13	.328
	2		11.32	.406
	3		5.60	.554
	4		16.15	.446
	5		9.28	.414
		Site Average =	11.70	0.430
2	1		7.55	.355
	2		5.96	.490
	3		8.54	.435
	4		11.08	.411
		Site Average =	8.28	0.423

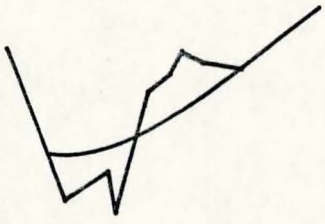
line was applied to the data to smooth out any large irregularities in the data points (Figure 3). The "smoothed" data portrayed wider and deeper cross-sections than was found from the ground surveys. This may have resulted from the low quality imagery and ground truth utilized. A scaling ratio was developed from easily obtained channel measurements in order to adjust the aerial photography data. The average width of the ground cross-sections at a site was divided by the average width as determined from aerial photography data. This ratio was used to scale the horizontal distances. The vertical distances were scaled by the ratio of average maximum depth in the ground survey cross-section to the average maximum depth from the aerial photograph data. These scaling values are different comparing the two sites because the air base, and therefore, scale changes between sites. Once scaled, data sets were developed for the aerial photograph cross-section and an average p-A relationship developed for each site. The results of the scaling and comparison of a and b values is presented in Table 2. A plot of the average p-A relationships at each site is presented in Figure 4 for the range of data. The comparisons indicate that even with low quality aerial surveys a simple adjustment of data can provide realistic and relatively accurate results. Interestingly, though the scaling factors changed between sites, the ratio of horizontal to vertical scaling factors at the sites were relatively constant. It is anticipated that with better imagery a more accurate comparison could be made between ground and aerial surveys.



Cross Section 1



Cross Section 2



Cross Section 3

Scale -

1" horizontal = 40'

1" vertical = 20'

Figure 3. Original and smoothed cross sections for Site 2 as taken from aerial photographs.

Table 2. Comparison of ground truth and aerial surveys.

Site 1

	Average Width feet	Average Maximum Depth	$\bar{a}$	$\bar{b}$
Ground Truth	68.14	2.60	11.70	0.43
Aerial Surveys*	129.0	11.57	11.69	0.39
Scaling ratios	Horizontal = 0.528			
	Vertical = 0.225			

Site 2

Ground Truth	34.25	1.88	8.28	0.423
Aerial Surveys*	91.30	11.23	9.60	0.354
Scaling ratios	Horizontal = 0.375			
	Vertical = 0.167			

*Smoothed Data

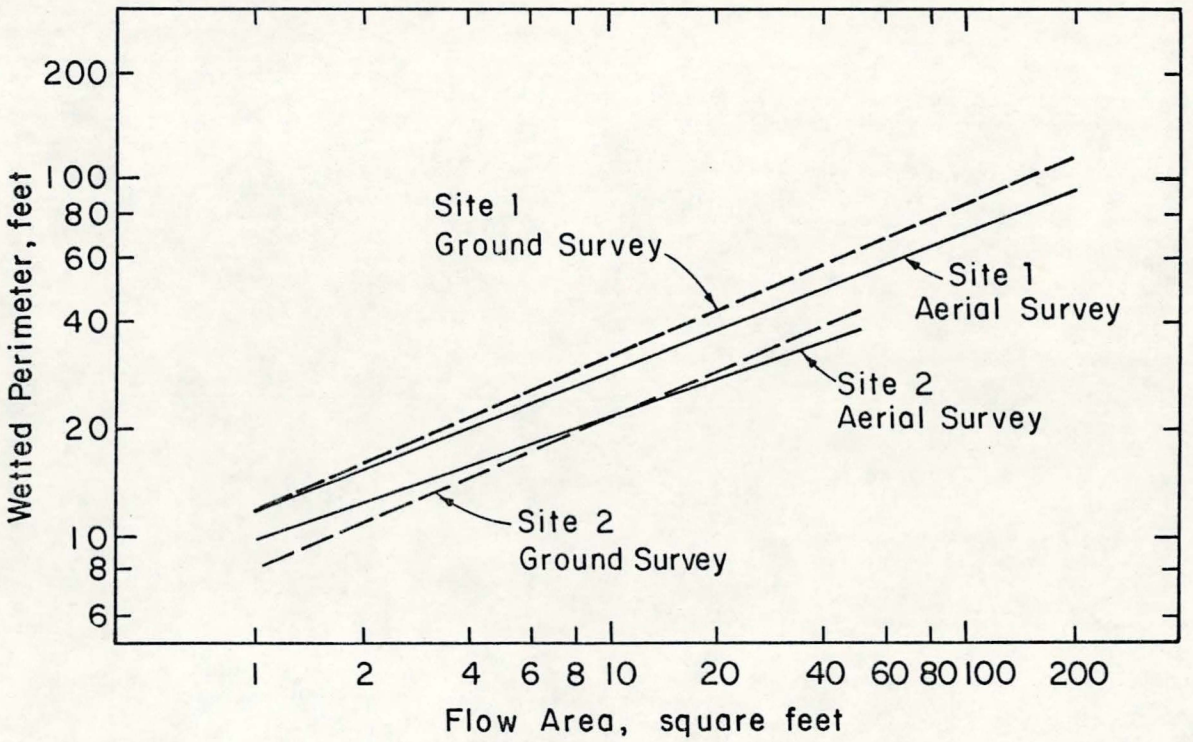


Figure 4. Wetted perimeter versus flow area for ground truth and aerial photography measurements.

V. PARAMETER SENSIVITY

5.1 Sensitivity of Wetted Perimeter Computation

Accuracy of measured data is important since data collectors need to know how precisely a measurement must be taken to do their job efficiently. Research scientists who use the data can help inform collection personnel regarding the degree of accuracy required. Consequently, research scientists must know the effects of errors in the data on values or parameters derived from the data. The error produced by incorrectly computing a and b parameters for Equation 2,

$$p = aA^b \tag{2}$$

can affect the calculation of wetted perimeter and subsequently water routing. The error produced in the wetted perimeter p can be estimated using differenetiation of the p and A relationship. The linear form given in Equation 3 can be differentiated to

$$\frac{dp}{p} = \frac{da}{a} + b\,\frac{dA}{A} + db\ \ln A \tag{14}$$

where dp, da, and dA are the differential increments of the respective variables. The term dp/p can be defined as the fractional change in p produced by fractional changes in other variables. Since b is less than 1.0 and is usually near 0.5, a change in A only results in about one-half the change in p. If A is constant then the term dA/A is zero and the error is derived from the terms da/a and db ℓn A. The error in p can then be estimated knowing the error in a and the estimated range in b. For example, at Site 1 the average value of a was 11.70 with a standard deviation of 4.55 (Table 1). A relative error dp/p may be assigned to this value as 4.55/11.70 = 0.39. Similarly, the mean b is 0.43 and the standard deviation is 0.082. A

db value can be estimated at about 0.08. If the cross sectional flow area is 100 square feet, the error in the wetted perimeter is equal to the sum of the errors in dp/p or dp/p = 0.39 + 0.08 (ℓnA) = 0.76 or 76 percent. However, this computation of error is incorrect because of the relationship between a and b. In general, as a increases b decreases which compensates the errors and results in an overall change in dp/p of only ± 2 percent. This is demonstrated by using values from Table 1. Assuming A equals 100 square feet, which is about the maximum area at the site, the wetted perimeter computed using average a and b parameters is 85 feet. Using the minimum value of a equal to 5.60 with b equal to 0.554, the wetted perimeter becomes 72 feet. Similarly, the minimum value of b equal to 0.328 corresponds to the near maximum value of a equal to 16.13 that yields a wetted perimeter of 73 feet. The maximum error in this case is only 15 percent, much less than what may occur if a and b were not inversely related. The average p value using all five sections at Site 1 is 81 feet, comparing very well with the value computed using the average a and b parameters. Similar comparisons can be made for Site 2. It should be noted that the greater the number of cross-sections measured, the more representative will be the values of a and b. Offsetting errors in a and b plus measurements from at least three cross sections should lessen errors in the computed p value.

5.2 Sensitivity of Water Routing Computation

Water routing is affected by errors in the p and A relationship. Simons, Li, and Stevens (1975) describe water routing of channel flow using the kinematic wave approximation to the momentum equation. The cross-sectional flow area can be estimated by

$$A = \alpha Q^{\beta} \tag{15}$$

where Q is water discharge and α and β are parameters derived from channel shape, friction slope, and channel roughness. Flow area is related to discharge because an error in Q produces a smaller error in A rather than if the inverse relationship were employed. If the Darcy-Weisbach friction factor is used, the value of α for channel flow is found from

$$\alpha = \left(\frac{Ka}{8gS_f}\right)^{\frac{1}{3-b}} \tag{16}$$

and β is determined from

$$\beta = \frac{2}{3-b} \tag{17}$$

where K is a friction factor, g is the acceleration of gravity, S_f is the friction slope of the channel, and a and b are parameters from Equation 2. Inspection of Equation 15 shows that errors in a and b affect only flow area not discharge. Therefore, water yield and peak discharge will not be altered by errors in the a and b parameters. An error in area, however, will affect the computed stage or depth at the cross-section, the mean velocity, and sediment discharge calculations. Analysis of Equation 15 with Equations 16 and 17 also indicate the error in area produced by errors in a and b are a function of field conditions. Errors from a are related to the value of b. If b is assumed at 0.5, the relative error in the area is 0.4 times the error in a. As b increases, the error in area caused by a also increases. This error in area will range from about one-third to about one-half of the error in parameter a. The error in area caused by an error in parameter b is a function of a, K, Q, and S_f (defined above). Positive errors in b produce positive errors in the flow area. The magnitude of the error is directly proportional to a, K, and Q and

inversely proportaional to S_f; therefore, an estimate of the error depends on field conditions and can vary with changing discharge. For example, if a equals 11.7, b equals 0.43, Q equals 700 cfs, S_f equals 0.06, K equals 0.4, and db equals 0.08, the error dA/A is about 0.03. Different conditions would produce different errors.

5.3 Errors in Parameters Related to Number of Measurements

As the number of sections at a site increase, the more accurate is the average or "true" parameter. For example, Table 1 lists the computed a and b parameters for each section at Site 1. As the number of sections increases, the difference between the "true" average value and the average of the section values decreases. At three sections the difference is relatively small indicating that this is an acceptable number of sections to measure in order to reduce errors and conserve time.

The channel geometry at the stream mouth controls the water and sediment discharge leaving the watershed. Therefore, it is important that enough cross-sections be measured at the mouth in order to develop a representative p and A relationship.

Similarly, representative relationships based on a sufficient number of cross-sections should also be developed at the confluences of major tributaries. Relationships upstream from the mouths or confluences aid in determining intermediate hydraulic characteristics. These characteristics can be used to track sediment and water discharge as well as account for channel aggradation and degradation. In general, a minimum of three widely separated sites on the main stem and each major tributary should be measured in order to provide a representative change in cross-sectional characteristics.

Errors in the parameters of the p and A relationship can have an effect on computing some hydraulic characteristics of a cross-section. Computed water discharge is unaffected but computed sediment transport may be altered. Errors in one p and A relationship parameter may be compensated by errors in the other parameter. A sufficient number of sites and cross-sections at each site will help provide a more accurate representation of the p and A relationship.

VI. SUMMARY AND CONCLUSIONS

In this report two methodologies were presented for determining parameters essential for mathematical modeling of watersheds. One method is based on ground surveys, the other on ground and aerial surveys. Both techniques are available to most data collection groups. The ground survey technique is best for small or accessible watersheds while the ground-aerial surveys may be more appropriate for larger or more inaccessible watersheds.

The example of application and comparison of ground and aerial survey derived parameters support the hypotheses that aerial surveys are a realistic method for collecting this type of data. However, it should be remembered that the adequacy of the aerial survey data is highly dependent on the ground control quality.

Errors in the a and b parameters in the p and A relationship do not cause errors in water discharge, but do cause errors in computing some hydraulic characteristics. Errors in the calculation of one parameter can be offset by errors in the other. Errors can be reduced if a sufficient number of sites and cross-sections are measured.

REFERENCES

Li, R. M., "Mathematical Modeling of Response from a Small Watershed." Dissertation, Colorado State University, Fort Collins, Colorado, 1974.

Li, R. M., D. B. Simons, and M. A. Stevens, "Morphology of Cobble Streams in Small Watersheds," Journal of Hydraulics Division, ASCE Vol. 102, No. Hy8, August 1976.

Simons, D. B., R. M. Li, and M. A. Stevens, "Development of Models for Predicting Water and Sediment Routing and Yield from Storms on Small Watersheds," prepared for USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Flagstaff, Arizona, 1975.

Appendix A

Computer Program CHANGEO

This appendix includes a list of the computer program CHANGEO. This program is used to determine wetted perimeter-flow area relationships for channels without overbank flow. Using paired horizontal and vertical channel measurements, program CHANGEO sets flow depths and then computes the corresponding wetted perimeter and flow area. Wetted perimeter-flow area data pairs are used to calculate a power function relationship.

Input sequence from program CHANGEO is given below.

Card	Variable	Column	Format	Contents
1	TITLE	1-80	20A4	Name of study area
2	NSP	1-10	I10	Number of Cross Sections $\square$ 50
	NAP	11-20	I10	Number of p-A pairs to be computed $\leq$ 50
	CONX	21-20	F10.0	Conversion factor for horizontal measurement if needed
	CONY	31-40	F10.0	Conversion factor for vertical measurement if needed
*3	NP(1)	1-10	I10	Number of horizontal and vertical measurements in Section 1
	NP(2)	11-20	I10	Number of horizontal and vertical measurements in Section 2
	etc.	etc.		Up to NSP
*4	(XI(1), YI(1))	1-10	(F5.0,F5.0)	Horizontal and vertical channel data pair Number 1 for one section
	(XI(2), YI(2))	11-20	(F5.0,F5.0)	Second set of data pairs
	etc.	etc.		Up to NP sets ($\leq$ 50)

*Card is repeated until all data is input.

Output from CHANGEO consists of titles, input horizontal and vertical channel measurement data pairs, adjusted data used in computing P-A data pairs, least squares best fit regression line using natural logarithms, a correlation coefficient, and a standard error of estimate. Certain error messages are printed if input channel measurements are erroneous.

Listing for Program CHANGEO

```
      PROGRAM CHANGEO (INPUT,OUTPUT)
C     THIS PROGRAM IS DESIGNED TO ESTIMATE WETTED PERIMETER-FLOW AREA
C     RELATION, P-A RELATION, FOR A NATURAL CHANNEL FROM MEASURED DATA
      DIMENSION TITLE(20),NP(50),XI(50),YI(50),XF(50),YF(50),A(50),P(50)
      DIMENSION X(50),Y(50)
C     INPUT THE NAME OF THE STUDY AREA
      READ 501, TITLE
  501 FORMAT(20A4)
      PRINT 601, TITLE
  601 FORMAT(1H1////25X,20A4///)
C     INPUT THE NUMBER OF CROSS SECTIONS AND THE NUMBER OF VERTICALS
C     TO BE USED IN EACH CROSS SECTION FOR DEVELOPMENT
C     OF THE P-A RELATION. NAP IS USUALLY SET AT 20.
C     ALSO INPUT THE CONVERSION FACTORS IF THE X-Y DATA ARE
C     NOT IN THE SAME UNITS
      READ 502, NSP,NAP,CONX,CONY
  502 FORMAT(2I10,2F10.0)
C     INPUT THE NUMBER OF MEASUREMENTS AT EACH CROSS SECTION
      READ 503, (NP(I),I=1,NSP)
  503 FORMAT(8I10)
      DO 10 I=1,NSP
      NDP=NP(I)
C     INPUT THE DATA POINTS AT THE CROSS SECTION
      READ 504,((XI(J),YI(J)),J=1,NDP)
  504 FORMAT (8(F5.0,F5.0))
      PRINT 602, I
  602 FORMAT(40X,*CHANNEL SURVEY DATA FOR CROSS SECTION*I5//)
      PRINT 603, (YI(J),J=1,NDP)
      PRINT 603, (XI(J),J=1,NDP)
  603 FORMAT(10X,16F7.1)
C     EXTRAPOLATION OF END POINTS TO FIND VERTICALS EQUAL TO ZERO
      IF(YI(1) .EQ. 0.) GO TO 1
      YEXT=YI(2)-YI(1)
C     IF END POINTS CANNOT BE EXTENDED PRINT OUT ERROR AND CONTINUE
      IF(YEXT .LE. 0.) PRINT 99
   99 FORMAT(30X*ERROR IN DATA*//25X*END POINT CANNOT BE EXTENDED*/
     125X*TO FIND VERTICAL EQUAL TO ZERO*/
     225X*FOR THIS CROSS SECTION*/)
      IF(YEXT .LE. 0.) GO TO 10
      XADD=YI(1)*(XI(2)-XI(1))/(YI(2)-YI(1))
      XF(1)=0.
      YF(1)=0.
      DO 20 J=1,NDP
      K=J+1
      XF(K)=XI(J)+XADD
      YF(K)=YI(J)
   20 CONTINUE
      NDP=NDP+1
      GO TO 2
    1 DO 25 J=1,NDP
      XF(J)=XI(J)
      YF(J)=YI(J)
   25 CONTINUE
    2 IF(YF(NDP) .EQ. 0.) GO TO 3
      MDP=NDP-1
      YEXT=YF(MDP)-YF(NDP)
      IF(YEXT .LE. 0.) PRINT 99
      IF(YEXT .LE. 0.) GO TO 10
      XADD=YF(NDP)*(XF(NDP)-XF(MDP))/(YF(MDP)-YF(NDP))
```

Listing for Program CHANGEO (continued)

```
      NDP=NDP+1
      MDP=NDP-1
      XF(NDP)=XF(MDP)+XADD
      YF(NDP)=0.
    3 CONTINUE
C     FIND MAXIMUM OF MEASURED DATA AND ADJUST UNITS IF NEEDED
      IF(CONX .LE. 0.0) CONX=1.0
      IF(CONY .LE. 0.0) CONY=1.0
      YMAX=0.
      DO 30 J=1, NDP
      XF(J)=XF(J)*CONX
      YF(J)=YF(J)*CONY
      IF(YF(J) .GT. YMAX) YMAX=YF(J)
   30 CONTINUE
      PRINT 604
  604 FORMAT(50X, *ADJUSTED DATA*)
      PRINT 603, (YF(J), J=1, NDP)
      PRINT 603, (XF(J), J=1, NDP)
      DY=YMAX/FLOAT(NAP)
      YIN=0.
C     DETERMINE P AND A AT EACH OF NAP VERTICAL LEVELS
      DO 40 J=1, NAP
      YIN=YIN+DY
      YCOM=YMAX-YIN
      AREA=0.
      WPER=0.
C     DETERMINE P AND A BETWEEN EACH PAIR OF DATA POINTS
      DO 50 K=2, NDP
      KM=K-1
      IF(YCOM .LT. YF(KM) .OR. YCOM .LT. YF(K)) GO TO 12
      GO TO 50
   12 XDEF=XF(K)-XF(KM)
      IF(YCOM .LT. YF(KM) .AND. YCOM .LT. YF(K)) GO TO 14
      IF(YCOM .LT. YF(KM)) GO TO 16
      YDEF=YF(K)-YF(KM)
      YDEL=YF(K)-YCOM
      GO TO 18
   16 YDEF=YF(KM)-YF(K)
      YDEL=YF(KM)-YCOM
   18 SLOPE=XDEF/YDEF
C     COMPUTE P AND A FOR A TRIANGULAR AREA
      WPER=WPER+YDEL*SQRT(1.+SLOPE*SLOPE)
      AREA=AREA+0.5*YDEL*YDEL*SLOPE
      GO TO 50
C     COMPUTE P AND A FOR A TRAPEZOIDAL AREA
   14 WPER=WPER+SQRT((YF(K)-YF(KM))**2+XDEF*XDEF)
      AREA=AREA+0.5*(YF(K)+YF(KM)-2.*YCOM)*XDEF
   50 CONTINUE
      A(J)=AREA
      P(J)=WPER
      X(J)=ALOG(AREA)
      Y(J)=ALOG(WPER)
   40 CONTINUE
      PRINT 605
  605 FORMAT(45X,*FLOW AREA-WETTED PERIMETER RELATION*)
      PRINT 606, (A(J), J=1,NAP)
      PRINT 606, (P(J), J=1, NAP)
  606 FORMAT(10X, 10F12.5)
C     DETERMINE P-A RELATION BY LEAST SQUARES SUBROUTINE
      CALL LSQ(NAP,X,Y)
   10 CONTINUE
      STOP
      END
```

Listing for Program CHANGEO (continued)

```
      SUBROUTINE LSQ(N,X,Y)
C     THIS SUBROUTINE DETERMINES A P-A RELATION USING A LEAST SQUARE
C     FIT TO THE LOG VALUES
      DIMENSION X(50),Y(50),YR(50)
      SUMX=0. $ SUMXX=0. $ SUMY=0. $ SUMYY=0. $ SUMXY=0.
      SUMA=0. $ SUMB=0. $ SUMC=0. $ SUMD=0.
      DO 40 I=1, N
      SUMX=SUMX+X(I)
      SUMY=SUMY+Y(I)
      SUMXX=SUMXX+X(I)*X(I)
      SUMXY=SUMXY+X(I)*Y(I)
   40 CONTINUE
      FX=SUMX/FLOAT(N)
      FY=SUMY/FLOAT(N)
C     DERIVATION OF EQUATION
      B=(SUMXY-FLOAT(N)*FX*FY)/(SUMXX-FLOAT(N)*FX*FX)
      A=FY-B*FX
C     CALCULATION OF COEFFICIENT OF CORRELATION
      DO 2 I=1, N
      SUMA=SUMA+(X(I)-FX)*(Y(I)-FY)
      SUMB=SUMB+(X(I)-FX)**2
      SUMC=SUMC+(Y(I)-FY)**2
      YR(I)=A+B*X(I)
    2 CONTINUE
      RC=SUMA/SQRT(SUMB*SUMC)
C     CALCULATION OF STANDARD ERROR OF ESTIMATE
      DO 3 I=1,N
      SUMD=SUMD+(Y(I)-YR(I))**2
    3 CONTINUE
      SBAR=SQRT(SUMD/(FLOAT(N)-2.))
      PRINT 60, A,B,RC,SBAR
   60 FORMAT(/10X,*THE REGRESION LINE*5X,*LN P =*F10.6* +*F10.6* LN A*/
     110X*CORRELATION COEFFICIENT=*F10.6/10X*STANDARD ERROR OF ESTIMATE=
     2*F10.6//)
      RETURN
      END
```

Appendix B

This appendix contains a sample input to and output from program CHANGEO. Smoothed data for Site 1 aerial surveys are used.

Input for Program CHANGEO is given below.

Variable		Contents
TITLE	-	Woods Canyon Creek Smoothed Data Site 1
NSP	-	3
NAP	-	20
CONX	-	0.523
CONY	-	0.225
NP	-	14, 15, 15
XI, YI	-	Shown on following output

The first set of numbers output is horizontal distances followed vertical distances. The second output is adjusted data converted to common units and extended to bank or vertical distance origin if needed. The third set is flow area and wetted perimeter pairs. All total flow areas are output first, then all corresponding wetted perimeters. Following these data sets is the equation of best fit line, a correlation coefficient, and a standard error of estimate.